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A novel evacuation passageway formed by a breathing air supply zone combined with upward ventilation

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HIGHLIGHTS

- BTES can be used to create a safe, smoke-free evacuation passageway out of the tunnel.
- BTES is optimized in this study.
- The influence of HRR, fire source location and detection time are discussed.

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ABSTRACT

With the development of transportation, the tunnel has become one of the important facilities of railway, highway and subway transportation. However, fire hazards occurring inside the tunnel may incur huge numbers of casualties and property losses. In this paper, a breathing air supply zone combined with an upward ventilation assisted tunnel evacuation system (BTES) is introduced. It can be used to create a safe, smoke-free evacuation passageway out of the tunnel. The BTES is optimized to achieve high-performance. The impacts of heat release rates, fire source locations and fire detection times are also discussed.

The carbon monoxide (CO) concentrations found when utilizing the BTES were significantly lower than that found when utilizing the traditional ventilation system. An obvious, clean evacuation passageway was created by the BTES. The maximum CO concentrations in the BTES evacuation passageway were below 10 PPM throughout the entire combustion process. A larger CO concentration gradient in the vertical direction was detected with the BTES than that found in other ventilation systems. This finding means that the lower part of the tunnel has a lower CO concentration with the BTES, which benefits the evacuation process. The impacts of fire source locations and fire detection times were

1. Introduction

With the development of transportation, the tunnel has become one of the important facilities of railway, highway and subway transportation [1]. However, fire hazards occurring inside the tunnel may incur huge numbers of casualties and property losses, such as those in Burnley, Austria in 2007 [2], Frejus, France/Italy in 2005, Dague, Korea in 2003 [3] and

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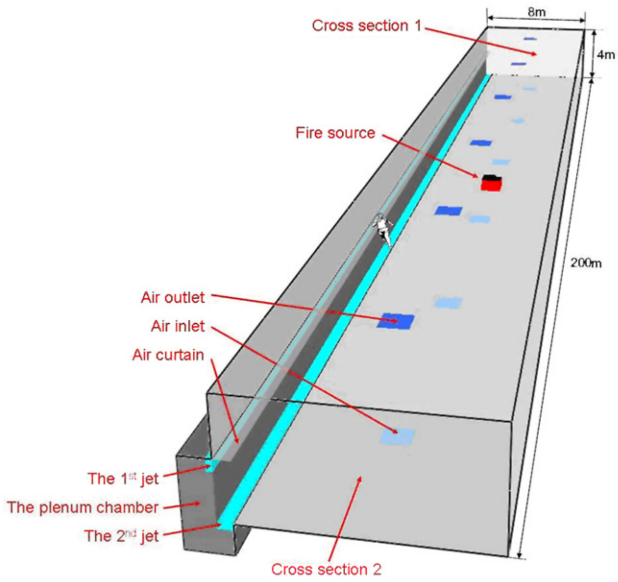

Fig. 1. The geometry of the tunnel.

Gotthard, Switzerland in 2001 [4]. Hundreds of people were killed in those tunnel fires. Statistics have shown that smoke is the most fatal factor in fires, and about 85% of the people were killed by fire induced smoke [5]. In a tunnel fire, or other underground fires, more toxic carbon monoxide will be produced because of incomplete combustion due to the lack of oxygen. Additionally, because the tunnel is a narrow and enclosed space, the smoke infiltration can be very fast [6], making timely evacuation of the people even more difficult to accomplish [7–9].

To facilitate the evacuation of people during fires, five types of commonly used ventilation systems have been developed for usage in tunnels [10]. They are the longitudinal ventilation system, supply air semi-transverse ventilation system, exhaust air semi-transverse ventilation system, full transverse ventilation system and the natural ventilation system [11,12]. The primary objective of these ventilation systems is to reduce the smoke concentration in the tunnel. However, they actually reduce the average smoke concentration of the entire tunnel, rather than that of the lower part of the tunnel, used for human evacuation. As a result, the smoke concentration in the lower part of the tunnel is still at a very high level when utilizing the traditional ventilation systems [13,14].

As a matter of fact, it is not necessary to ensure that the entire tunnel space is clean, nor is it even necessary to ensure that the entire lower part of the tunnel space is clean [15]. It is only necessary to ensure that a safe, smoke-free evacuation path is clean [16–18]. Based on this, both breathing air supply zone ventilation and upward ventilation can be introduced into the tunnel ventilation system design. These two ventilation methods are types of personal ventilation. Personal ventilation is one of the three main building ventilation methods, along with mixing ventilation and displacement ventilation. Personal ventilation supplies clean air directly to the breathing zone, and has been proven to be more effective than mixing ventilation or displacement ventilation [19,20]. All of the traditional tunnel ventilation systems mentioned above can be categorized into either mixing or displacement type building ventilation methods. None of these traditional tunnel ventilation systems mentioned above can be categorized as a personal type of building ventilation method.

In this paper, a breathing air supply zone that was combined with an upward ventilation assisted tunnel evacuation system (BTES) is introduced. The BTES can be used to create a safe, smoke-free evacuation passageway out of the tunnel, bringing a new perspective to ventilation system design and human evacuation systems for usage during tunnel fires. The BTES is optimized in this study, and the influence of the heat release rate, the fire source location and the fire detection time are also discussed.

2. Study object

The tunnel chosen for this study is a typical rectangular tunnel, as shown in Fig. 1. The size of this tunnel is 200 m × 8 m × 4 m. The BTES is installed along one side of this tunnel. When it is in operation, people can evacuate through the evacuation passageway created by the BTES.

The BTES includes four sections: the plenum chamber, the air curtain, the 1st jet and the 2nd jet, as seen in Fig. 2. The plenum chamber is installed at the corner of the tunnel connected with the 1st jet and the 2nd jet. The width of both jet is 0.5 m. The 1st jet is installed in the side wall of the tunnel, at a height of 1.5 m from the tunnel floor, and it is used to ensure a clean breathing zone. The two jets form the breathing air supply zone when combined with upward ventilation. In addition, the installed height of air curtain is 2 m.

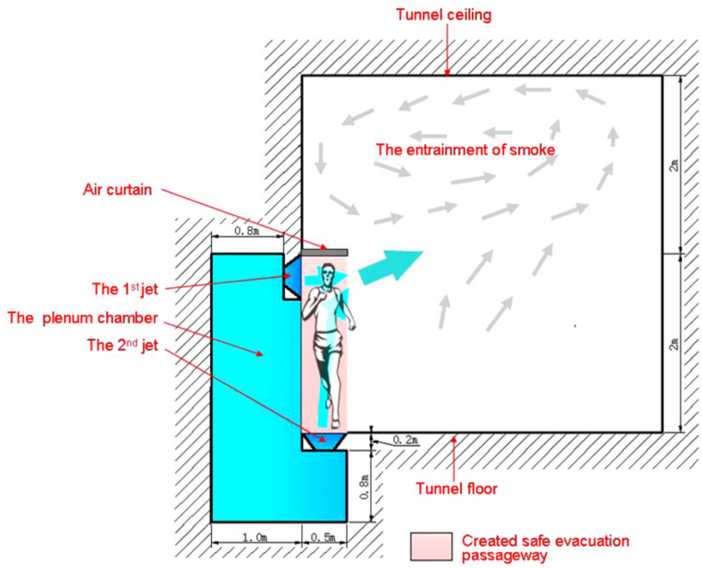

Fig. 2. Cutaway view of the novel evacuation passageway consisting of a breathing air supply zone combined with upward ventilation.

When a fire occurs in the tunnel, the smoke will first fill the entire upper space of the tunnel, and then spread downward. The smoke spreading downward has a certain momentum. The air curtain at the upper edge of the 1st jet will offset that momentum, preventing the smoke from flowing directly into the evacuation passageway. The velocity of the fire-induced smoke is random and pulsating, so the air curtain cannot stop 100% of the smoke from flowing into the evacuation passageway. The supply air from the 2nd jet is responsible for maintaining a positive pressure environment and for pushing any infiltrating smoke out of the evacuation passageway. In addition, the duct that is connected to the plenum chamber is fan powered and leads to the outside.

3. Ventilation systems

Over the past fifty years, five kinds of ventilation systems were developed to control fire-induced smoke inside of tunnels. They are the longitudinal ventilation system, supply air semi-transverse ventilation system, exhaust air semi-transverse ventilation system, full transverse ventilation system and the natural ventilation system [11,12], see Fig. 3.

Natural ventilation is as simple as the name implies. The movement of air is controlled by the buoyancy of the smoke, caused by the temperature difference between the hot smoke and the surrounding air. The piston effect is another driving force that is created by moving traffic pushing smoke through the tunnel. However, this effect is minimized during fire conditions.

Longitudinal ventilation is similar to natural ventilation, with the addition of mechanical fans. In its most basic configuration, the air flow moves from the tunnel entrance portal to the exit portal within the main tunnel cross section area, without any separate ventilation ducts along the tunnel.

Semi-transverse ventilation also makes use of mechanical fans for movement of air, but it does not use the tunnel itself as the ductwork. A separate plenum or duct system is added either above or below the tunnel, with ventilation shafts that allow for uniform distribution of air into or out of the tunnel. This plenum or duct system is typically located above a suspended ceiling, or below a structural slab, within a tunnel with a circular cross-section. It should be noted that there are two variations of the semi-transverse system. One variation is the supply air system, and the other is the exhaust air system. Both systems are actually half of the full transverse ventilation system, as they only need either a supply air or exhaust air system, while the full transverse ventilation system needs both supply air and exhaust air systems.

Full transverse ventilation uses the same components as semi-transverse ventilation, but it incorporates supply air and exhaust air systems together over the same length of the tunnel. The presence of supply and exhaust ducts allows for a pressure difference between the roadway and the ceiling, therefore, the air flows transverse to the tunnel length and is circulated more frequently.

All of the five ventilation systems we mentioned above are contained in the object tunnel for comparing to the performance of the BTES.

4. Simulation method

The CFD software employed to carry this study is Fire Dynamics Simulator (FDS). It is a free software developed by the national institute of standards and technology (NIST) of the United States. It has been widely used in the field of fire safety to

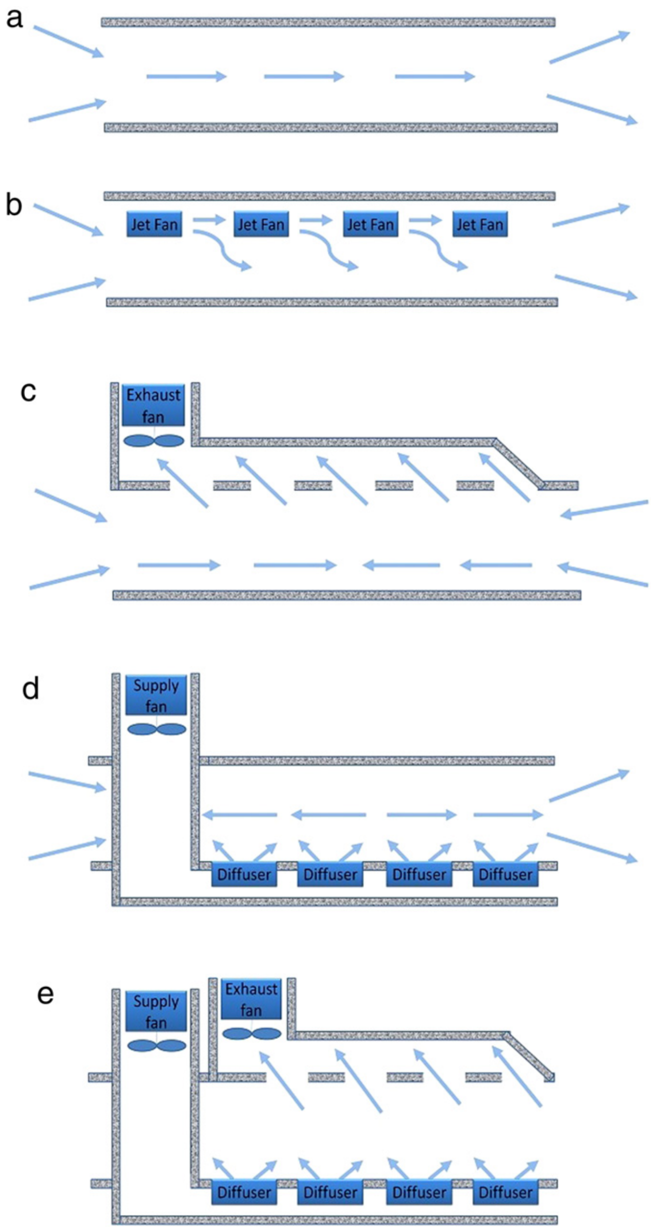

Fig. 3. The existing tunnel ventilation systems: (a) natural ventilation system, (b) longitudinal ventilation system, (c) exhaust air semi-transverse ventilation system, (d) supply air semi-transverse ventilation system, (e) full transverse ventilation system.

predict fire-induced smoke movement [21]. The detail settings of boundary condition, turbulent airflow model, fire sources and combustion model are also discussed in this section.

4.1. Boundary condition

According to the previous study [13,22], the boundary conditions of the above mentioned ventilation systems can be seen in Table 1. It should be noted that *Open* indicates that the inner smoke can freely move out of the tunnel through this boundary [21]. The number inside of the brackets is the velocity value of the smoke. A plus sign (+) indicates that fresh air is supplied into the tunnel, while the minus sign (−) indicates that smoke was exhausted from the tunnel. In addition, the size of the air inlets and outlets are all 2.5 m × 2 m, and the widths of the 1st and 2nd jets are 0.5 m.

In order to predict the temperature increase on the tunnel wall due to the radiant and convective heat transfers from the surrounding smoke, L.H. Hu (2008) used the thermally thick boundary conditions, rather than fixed temperatures or heat-flux boundary conditions [23] in their study. It proved that the predicted result can be more accurate with thermally thick

Table 1
Boundary condition of the vents for different ventilation systems.

System name	The 1st jet	The 2nd jet	Air curtain	Air inlet	Air outlet	Cross section 1	Cross section 2
BTES	VI(0.7 m/s)	VI(0.3 m/s)	Yes	No	No	"Open"	"Open"
Longitudinal ventilation	No	No	No	No	No	VI(+2.0 m/s)	"Open"
Supply-air semi-transverse ventilation	No	No	No	VI(+3.5 m/s)	No	"Open"	"Open"
Exhaust-air semi-transverse ventilation	No	No	No	No	VI(−3.5 m/s)	"Open"	"Open"
Full-transverse ventilation	No	No	No	VI(+3.5 m/s)	VI(−3.5 m/s)	"Open"	"Open"
Natural ventilation	No	No	No	No	No	"Open"	"Open"

Note: VI = Velocity inlet. "−" means exhaust air from the tunnel, while "+" means supply fresh air to the tunnel.

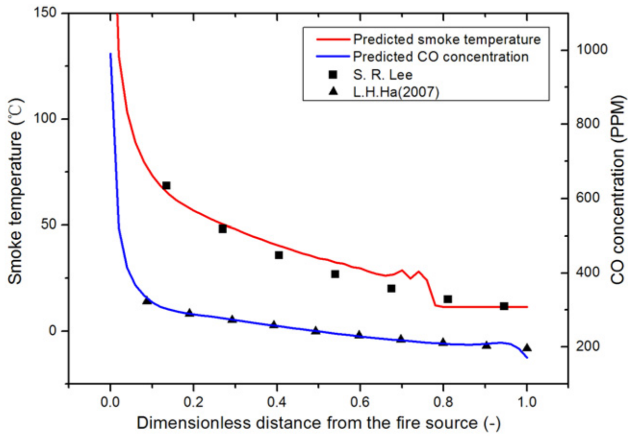

Fig. 4. Parameter validation with the experimental data.

boundary conditions. This study also applies thermally thick boundary conditions to consider the temperature increase of the tunnel walls and ceiling, as a result of radiant and convective heat transfers from fire-induced smoke. The material of the tunnel walls and ceiling is concrete with conductivity of 2.0 W/m/K density of 2400 kg/m^3 and specific heat of 0.9 kJ/kg/K [21].

4.2. The turbulent airflow model

Three main turbulent airflow models: Reynolds averaging Navier–Stokes equation (RANS), Direct numerical simulation (DNS) and Large Eddy Simulation (LES) are developed to predict the transportation of fire-induced smoke [21]. Many studies have been addressed to compare the advantages and disadvantages among those models. LES method can resolve turbulent flow structures and predict instantaneous flow characteristics which are especially important in the simulations involving combustion [24,22]. Based on this, LES, which is more computational cheap than DNS and more effective than RANS, was utilized in this study.

While carrying LES, two parameters Turbulent Prandtl number (Pr) and Turbulent Schmidt number (Sc) are very important for they directly determine the accuracy of the predicted results, especially for the smoke temperature [25]. Corresponding to the previous study, the Pr and Sc are respectively adopted to be 0.2 and 0.5 [26]. Under this setting, the predicted smoke temperature was verified with the experimental data, and good agreement was achieved, see Fig. 4a [23].

Radiant heat transfer is an essential part of the heat transfer process under fire case. It is introduced in this study through the solution of radiation transport equation (RTE) which is solved using the FVM finite volume method.

Courant–Friedrich–Lewy (CFL) are used to justify the convergence of a numerical solution in the prediction of fire induced smoke transportation [27,28]. While using CFL, the computational time step is adjusted with each step during the entire iteration process to make value of CFL less than the criterion value of 1. This indicates that the CFL convergence condition was satisfied.

4.3. Fire sources and combustion model

The fire source is placed in the middle of the tunnel, with a dimension of $1 \times 1 \times 1$ m^3. The heat outputs were determined by the heat release rate (HRR) of the fire source. Seven types of fire sources with HRRs of: 5, 10, 15, 20, 25, 30 and 35 MW, which are most often used in the tunnel studies, have also been used in this study [14,26]. The fire source used was an actual diesel fire, using results of a study by Y.F. Wang (2009) [29].

A mixture-fraction-based combustion model was used in this simulation, as it extracts the local heat release rate (HRR) from the computed mixture fraction field [21]. The mixture fraction is partitioned into two components, such that the sum of these components is equal to the mixture fraction. Each component is tracked via a transport equation, and the conversion of mass from one component to the other, represents a reaction step and an associated release of energy.

While using mixture-fraction-based combustion model, the fraction of fuel mass converted into the soot-yield fraction, y_S, has been studied in the previous work [21]. The recommended value of y_S is given to be 0.1. With the aforementioned settings of y_S, it was found that the predicted CO concentration agrees well with the experiment data [30] as shown in Fig. 4b.

5. Result and discussion

5.1. System setting

Safety is truly the most important issue in a fire. To achieve fire safety, the BTES must be of high-performance. Therefore, the safety standards used to evaluate the performance of the BTES must be strict, and the system settings of the BTES must be optimized.

Because of the gusty and complicated character of tunnel fires, we do not know how long the fire will last or how long the people will take to evacuate. So the safety standard we chose to evaluate the BTES is that of the Occupational Safety and Health Administration (OSHA), [31] in which the superior limit of the standard of the CO concentration is 50 PPM, averaged over eight hours. Considering that people need to run to achieve evacuation during a fire, the superior limit of the CO concentration is adopted to be 10 PPM, which is 1/5 of the OSHA standard in this paper.

The CO concentration was collected within the evacuation passageway. Because the tunnel is 200 m long, the entire evacuation passageway has a very large volume. The smoke in the tunnel or in the created evacuation passageway was not evenly distributed. Locally high concentrations of CO could be very harmful to people's lives, so it is meaningless to collect the CO concentration utilizing a volume weighted mean. This is because the mean value could actually hide dangerous local CO concentrations. In this paper, the CO concentration collected is the maximum smoke CO concentration over the entire evacuation passageway [21]. Utilizing this method assures that if the collected CO concentration meets the safety standard that we mentioned above, we can be sure that the CO concentrations found anywhere along the entire evacuation passageway will also meet the standard.

In order to optimize the system settings of the BTES, the velocity ratio of the supply air from the jets and the minimum velocity magnitudes of the supply air were studied in this section.

5.1.1. The velocity ratio of the supply air from the jets

The two jets of supply air for the BTES have different functions, as we mentioned above. The 1st jet is installed in the side wall of the tunnel, and is used to ensure a clean breathing zone. The 2nd jet is responsible for maintaining a positive pressure environment, pushing infiltrating smoke back out of the evacuation passageway. So the supply air velocities of the 1st and 2nd jets are different, and the velocity ratio between the two jets should be optimized.

To obtain the optimal velocity ratio between the 1st and 2nd jet, nine types of velocity ratios between the two jets were tested here. Both supply air velocities of the 1st and 2nd jets varied from 0 to 1 m/s, as shown in Fig. 5a, where V1 means the supply air velocity of the 1st jet, while V2 means the supply air velocity of the 2nd jet. It was found that the minimum CO concentration level was at the point when the supply air velocity of the 1st jet was set to 0.3 m/s, and the supply air velocity of the 2nd jet was set to 0.7 m/s.

5.1.2. The minimum velocity magnitude of the supply air

The velocity magnitude of the supply air cannot increase indefinitely. Large velocity magnitudes involve high costs and implementation difficulties. The velocity magnitude needs to be just large enough for the CO concentration in the evacuation passageway to meet the safety standards. We refer to the velocity magnitude necessary to meet this requirement, as the minimum velocity of the supply air. Here, based on the optimal velocity ratio, the minimum velocity of the two jets with a heat release rate of 35 MW was obtained, as seen in Fig. 5b. It was found that the minimum velocities of the 1st and 2nd jets were 0.3 and 0.7 m/s, and by using these supply air velocities, the CO concentration in the created evacuation passageway was 9.88 PPM, which is below the required 10 PPM.

5.2. The effect of the heat release rate

Heat release rate (HRR) is the rate at which heat is generated by fire, and it is the main parameter that influences the CO concentration in the tunnel. Here, HRRs of 5, 10, 15, 20, 25, 30 and 35 MW were used to compare the ventilation system performance of the BTES for smoke control, to that of a longitudinal ventilation system, supply air semi-transverse ventilation system, exhaust air semi-transverse ventilation system, full transverse ventilation system and natural ventilation system. The value of CO concentration measured in the tunnel with BTES is the maximum value of the entire evacuation passageway. Other ventilation systems designs do not include such an evacuation passageway, but we obtained the CO concentrations in the same location, for ease of comparison. Comparisons with the ventilation systems we mentioned above, showed that the CO concentration with the BTES was significantly lower, as seen in Fig. 6. The maximum CO concentration in the evacuation passageway was below 10 PPM through the entire combustion process. With an HRR of 35, the CO

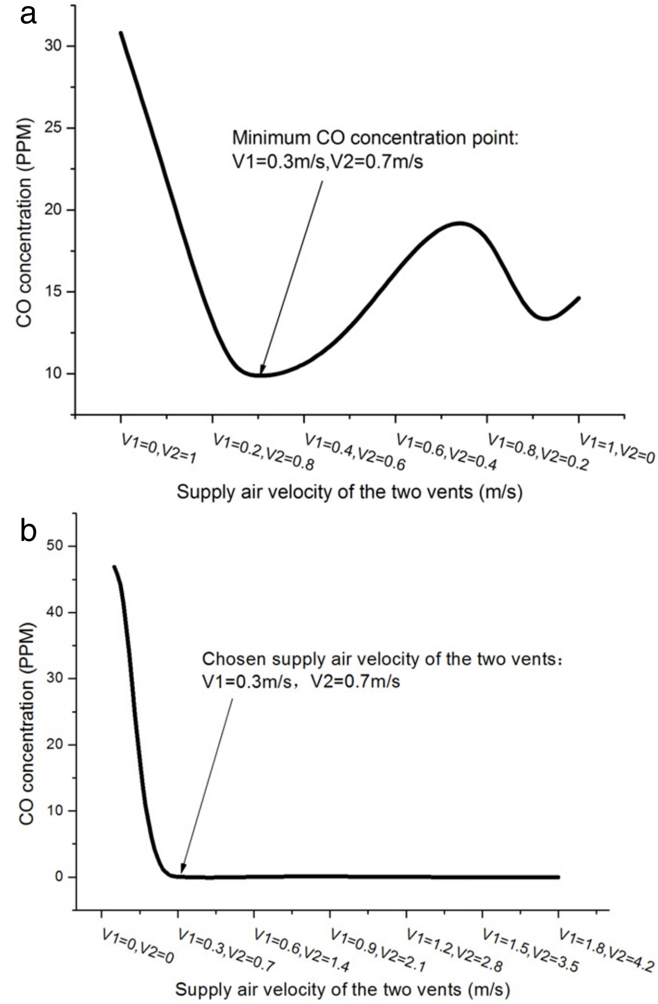

Fig. 5. Comparison of CO concentration in the evacuation passageway with: (a) different velocity ratio; (b) different velocity magnitude.

concentration with BTES was only 0.48% of the natural ventilation system measurement, 0.54% of the longitudinal ventilation system measurement (from the back side of the tunnel), 0.58% of supply air semi-transverse ventilation measurement, 0.76% of exhaust air semi-transverse ventilation measurement, and 0.80% of the full transverse ventilation system measurement.

An obviously clean passageway is created by the BTES as shown in Fig. 7. A larger CO concentration gradient in a vertical direction can be seen with the BTES than with other ventilation systems. That means the lower part of the tunnel has a very low CO concentration with BTES, and that benefits the evacuation process.

The longitudinal ventilation system has many advantages, including a smaller space requirement for ventilation ductwork and fewer initial capital costs. It can also be easily installed inside the tunnel [13]. However, it had difficulty in managing the smoke in the downstream end of the tunnel [32]. A basic characteristic of the longitudinal ventilation is that it creates a uniform, longitudinal stream of air, all along the tunnel. The clean air enters the tunnel from one portal, flows though the fire source, and takes the smoke with it. Therefore, the tunnel space after the fire source is totally polluted with the smoke. People can only evacuate from one end of the tunnel, while the other end of the tunnel is filled with smoke. That is not conducive to the effective evacuation of the occupants, as seen in Fig. 7b. Although the front of the tunnel is clean, the back end of the tunnel is as dirty as the tunnel with natural ventilation. The evacuation passageway created by the BTES, on the other hand, is clean throughout the entire tunnel, as seen in Fig. 7a. People can evacuate the tunnel safely from both ends of the tunnel, thus increasing the possibility of a complete evacuation.

The smoke distribution of the tunnel with the supply air semi-transverse ventilation system, exhaust air semi-transverse ventilation system, full transverse ventilation system and natural ventilation system are all similar. Although most of the smoke stays in the upper area of the tunnel, the CO concentration in the lower area of the tunnel is still larger than 300 PPM. This level of CO concentration is six times larger than the limit of the safety standard of OSHA, and it is extremely dangerous for the people in the tunnel.

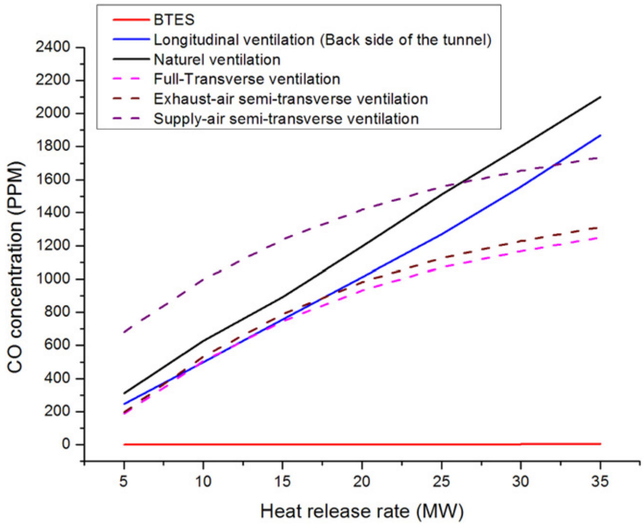

Fig. 6. Comparison of CO concentration in the tunnel for different ventilation systems.

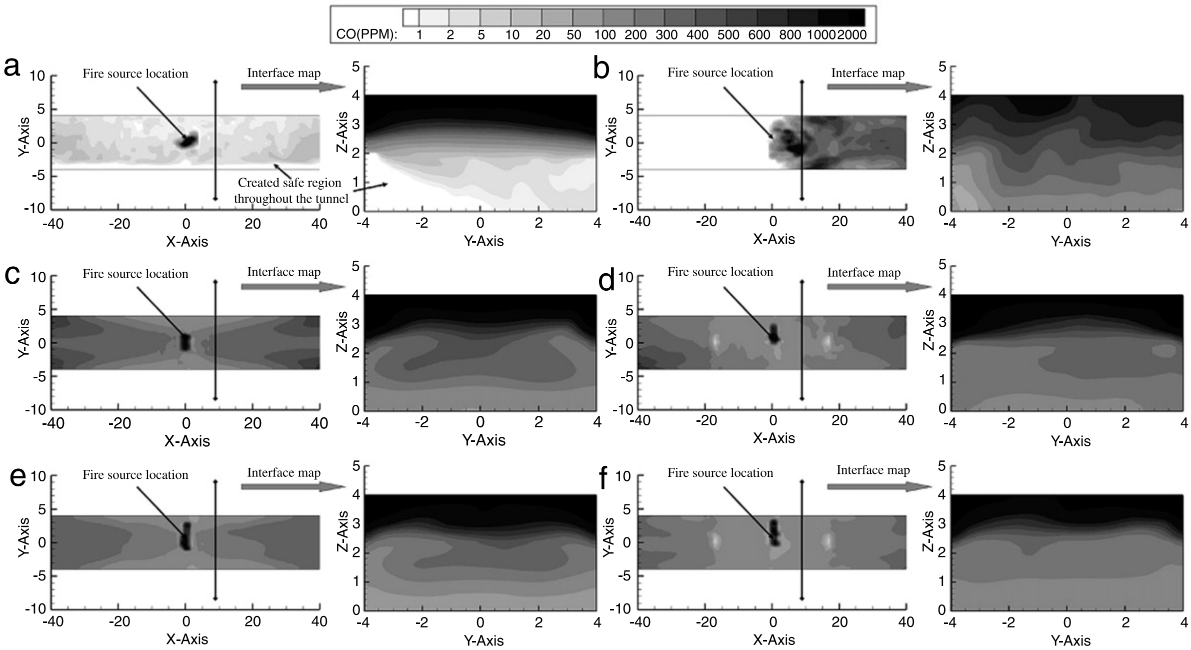

Fig. 7. CO concentration contour of the tunnel under different ventilation system: (a) BTES, (b) longitudinal ventilation system, (c) natural ventilation system, (d) supply air semi-transverse ventilation system, (e) exhaust air semi-transverse ventilation system, (f) full transverse ventilation system.

The reason for this phenomenon is that traditional ventilation systems considered the tunnel as a whole space. They made efforts to reduce the CO concentration of this whole space, rather than a smaller area that people could use specifically to evacuate. Although traditional ventilation systems can reduce the CO concentration of the whole space, the CO concentration in the lower area of the tunnel remains at too high a level. The BTES is based on the concept that it is only necessary to create a path large enough for people to evacuate the tunnel, while delivering adequate supply air to meet the safety requirements, in order to provide a safe, effective evacuation passageway.

5.3. The effect of the fire source location

The effect of the fire source location is very important for testing system reliability of the BTES. For different fire source locations, the smoke distribution in the tunnel is totally different. There were two fire source locations in the tunnel used to test the BTES. The first fire source was located in the evacuation passageway of the BTES, while the second fire source was

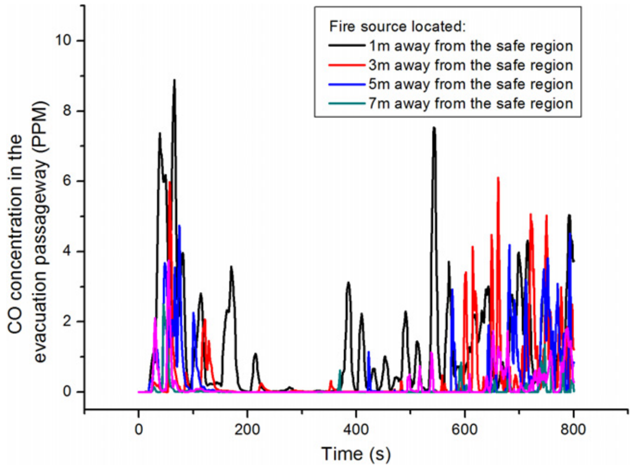

Fig. 8. Comparison of the CO concentration in the evacuation passageway for fire source location.

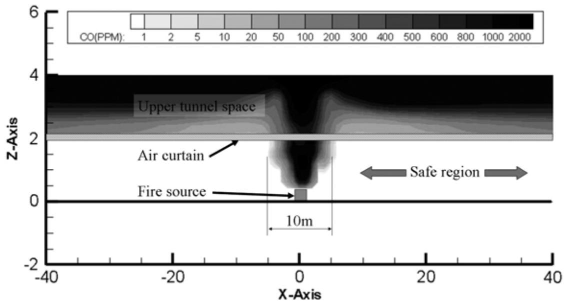

Fig. 9. CO concentration contour of the evacuation passageway during a fire.

located in the tunnel outside of the evacuation passageway. In the first instance, an 10 m long smoke area was formed in the evacuation passageway, as seen in Fig. 8. People could not pass through the smoke area, which cut the tunnel into two parts, however this did not hinder the evacuation process. People could still utilize the evacuation passageway, on their side of the smoke location, to exit to their end of the tunnel. The second fire source was located in the tunnel, out of the created evacuation passageway. There was little difference in the CO seen in the passageway with the different fire source, as shown in Fig. 9. This indicates that the CO concentration in the evacuation passageway is not sensitive to different fire source locations. It also suggests that the BTES has the capability to evacuate people in the tunnel, with different fire source locations.

5.4. Fire detection time

Fire detection time is the time from fire ignition to detection [33]. It is a key parameter because it directly determines when the ventilation system operates. When the fire detection time is not fast enough, the smoke will flow into the created evacuation passageway, and stay there. This makes it necessary to test whether the BTES can drive the smoke out of the created evacuation passageway in sufficient time.

Seven fire detection times, from 30 to 210 s were used to check the performance of the BTES. The BTES system is set to begin to operate immediately, when a fire is detected. If the CO concentration is below 10 PPM, we regard the evacuation passageway as clean. The time required to clean the evacuation passageway was recorded as seen in Fig. 10. It was found that the required time increased as the fire detection time increased, but the longest required time was less than 10 s.

6. Conclusion

A breathing air supply zone combined with an upward ventilation assisted tunnel evacuation system (BTES) is introduced in this paper. It can be used to create a safe evacuation path throughout the tunnel, which remains free of smoke. The system is optimized, and the supply air velocity of the 1st jet is set to be 0.3 m/s, while that of 2nd jet is set to be 0.7 m/s. According to this setting, the CO concentration in the created evacuation passageway is 10 PPM during a fire, with an HRR of 35 MW. The effect of the heat release rate, fire source location and fire detection times were also discussed.

It was also revealed that the CO concentration with a BTES is significantly lower than with a traditional ventilation system. The maximum CO concentration in the created evacuation passageway is below 10 PPM throughout the entire combustion

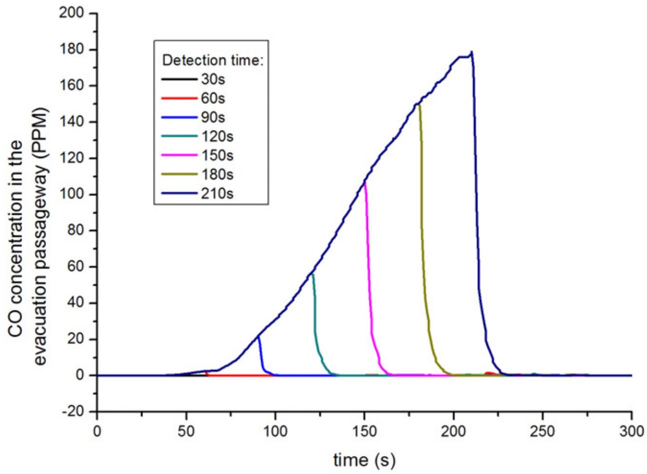

Fig. 10. Comparison of CO concentration in the evacuation passageway with different fire detection times.

process. With an HRR of 35, the CO concentration with the BTES is only 0.48% of natural ventilation, 0.54% of longitudinal ventilation (back side of the tunnel), 0.58% of supply air semi-transverse ventilation, 0.76% of exhaust air semi-transverse ventilation, and 0.80% of full transverse ventilation. An obviously clean passageway has been created by the BTES.

A larger CO concentration gradient in the vertical direction can be seen with the BTES than with other ventilation systems, which means the lower part of the tunnel has a very low CO concentration with BTES, and that benefits the evacuation process.

The effect of the fire source location was tested to ensure the system reliability of BTES. It found the CO concentration in the created evacuation passageway was not sensitive to the fire source location. It also suggests that a BTES has the capability to evacuate people in tunnels with different fire sources.

Seven different fire detection times, from 30 to 210 s, were used to check the performance of the BTES. The time that was required to clean the created evacuation passageway was recorded. It was found that the required time increased as the fire detection time increased, but the longest required time was less than 10 s.

Although BTES is proved to be effective to create safe region and help people evacuation theoretically and numerically, further experiment still need to be carried to speed up the popularization and application of BTES.

Acknowledgments

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